AN APPARATUS AND METHOD FOR ACCOMMODATIVE STIMULATION OF AN EYE AND SIMULTANEOUS IPSILATERAL ACCOMMODATIVE IMAGING

Background of the Invention

1. Technical Field

The present invention pertains generally to the field of visual accommodation, presbyopia and cataractogenesis, and, more particularly, to the acquisition of imaging information about an eye as it is simultaneously stimulated to undergo reversible changes of accommodative state.

2. Related Art

The crystalline lenses of the eyes undergo mechanical, physiological, morphological and refractive changes to adjust the total refractive power of the eyes to maintain sharp visual acuity whenever an object of regard is moved toward and away from the distance at which humans typically view reading material. The aggregate changes experienced by the crystalline lenses of the eyes to maintain sharp visual acuity is referred to as accommodation. At any given time the crystalline lenses and the eyes may be regarded as being in a state of accommodation. In transitioning from one stationary state of accommodation to another stationary state of accommodation, the crystalline lenses undergo a time-dependent process of dynamic accommodation. Heretofore, all attempts to acquire imaging information regarding dynamic accommodation have been unsuccessful, and imaging information has only been acquired

regarding the stationary states of accommodation between which dynamic accommodation is operative.

Summary of the Invention

The present invention is an apparatus comprising an accommodative stimulation device, an electromagnetic wave exposure device, and an imaging device, said apparatus acquiring imaging information about an eye by means of said electromagnetic wave exposure device and said imaging device, as said accommodative stimulation device simultaneously stimulates said eye to undergo at least one reversible accommodative transition from any first state of accommodation to any second state of accommodation, said accommodative stimulation device having an axis of projection that is substantially perpendicular to a visual axis of said eye, along which axis of projection an adjustable accommodative target is projected through a system of Badal optics, having a Badal optical axis coincident with said axis of projection, to strike a half-silvered mirror lying in a plane that forms an angle of about 45 degrees with said axis of projection and said visual axis of said eye.

The present invention advantageously overcomes limitations on the imaging of dynamic accommodation in the art of optics and ophthalmology by providing a technology that effectively "unconceals" dynamic accommodation, thereby lifting limitations that have confined knowledge of accommodation to the static endpoints of the dynamic accommodative process.

Brief Description of the Drawings

FIG. 1A is a schematic perspective illustration of a human eye.

FIG. 1B is a schematic perspective illustration of the crystalline lens and zonular apparatus of a human eye.

FIG. 1C is a schematic axial cross section of a human eye.

FIG. 2 is a schematic perspective illustration of a first nonlimiting exemplary embodiment of the invention.

FIG. 3 is a simplified schematic illustration of a slit lamp biomicroscope adapted to perform conventional ophthalmic imaging.

FIG. 4 is a schematic illustration of the principle of Scheimpflug imaging.

FIG. 5 is a schematic perspective illustration a accommodative stimulation device.

FIG. 6 is a schematic perspective illustration of a set of exchangeable target-image-forming masks.

FIG. 7 is a more detailed schematic perspective illustration of a first nonlimiting exemplary embodiment of the invention.

FIG. 8 is a block diagram of a second nonlimiting exemplary embodiment of the invention.

Detailed Description of the Invention

The detailed description refers to drawings in which like parts are designated by like numerals in the various views.

FIG. 1A is a schematic perspective illustration of a human eye **200**, set against an anatomical sagittal plane **240**, an anatomical axial plane **241** and an anatomical coronal plane

242, showing that the three-dimensional geometric shape of the human eye may generally be regarded as formed by the intersection of a first larger sphere **201** with a second smaller sphere (not shown in FIG. 1A), the visible portion of which protrudes from first sphere **201** as the anterior convexity of the eye -- the transparent cornea **204**. The generally circular line of intersection of these spheres forms the anatomic limbus **203**, a line of demarcation that circumscribes cornea **204**.

The cornea **204** is the eye's interface with the environment and its principal refractive structure. The cornea **204** is a trilamellar structure, having an anterior epithelium **204epi**, an interior stroma **204s**, and a posterior endothelium **204end**. The anterior-most point of the cornea is the corneal vertex **229**. Orientation about cornea **204** is determined by reference to meridians **227** in a plane parallel to coronal plane **242**, such as reference plane **230**. The meridian crossing from zero degrees to 180 degrees **231** and the meridian crossing from 90 degrees to 270 degrees **232**, as shown in FIG. 1A, are called principal meridians.

The larger second sphere **201** of the eye **200** outside of the limbus **203** forms the white shell of the eye **205**, whose posterior aspect **206** is entered by the optic nerve **207**. The shell of the eye **205** is also a tri-lamellar tissue, having an outermost tectonic layer known as the sclera **208**, a middle vascular layer known as the choroid **209**, and an innermost photosensitive layer known as the retina **210**. The choroid **209** and retina **210** are conjunctively referred to as the uvea. The most discriminatingly photosensitive region of the retina is confined to a region called the macula lutea **237**. An imaginary vector emanating from macular lutea **237** anteriorward, approximately perpendicular to coronal plane **242**, approximately along sagittal plane **240**, and

through cornea **204**, defines the visual axis **219** of the eye **200**.

Projecting radially inward from the shell **205** of the eye **200** circumferentially adjacent the limbus **203** is a circular disk-like diaphragm of tissue known as the iris **211**, whose innermost circular border forms the margin **212** of an aperture called the pupil **213**. The iris forms the aperture stop of the eye. Anatomically, the term "pupil" refers to either the actual or physical opening of the anatomic iris **211**, i.e., the physical opening of the aperture stop formed by the iris **211**.

When looking at the anatomical pupil **213**, from an external viewpoint directed into eye **200** through the cornea **204**, what is seen is a virtual image of the anatomical pupil **213** formed by cornea **204**. The anterior, through-the-cornea virtual image is called the "entrance" pupil (not shown in FIG. 1A). When looking at the anatomical pupil **213**, from an internal viewpoint directed anteriorward through crystalline lens **216** from behind, what is seen is a virtual image of the anatomical pupil **210** formed by crystalline lens **216**. The posterior, through-the-lens image of the anatomic pupil **213** is called the "exit" pupil (not shown in FIG. 1A). The entrance pupil appears anterior to the anatomic pupil **213**.

Immediately posterior and continuous with the iris **211** is the muscular ciliary body **214**, from which there are circumferentially elaborated a plurality of strands, called zonules **215**, projecting radially inward to tether the crystalline lens **216** just posterior to iris **211**. Zonules **215** insert onto a lens capsule **217** that envelopes the crystalline lens **216**. Zonules **215** insert onto lens capsule **217** along a circle generally coincident with the equator **218** of the crystalline lens **216**.

As shown in FIG. 1B, in the normal anatomic position, the lens **216** has the general form of an ellipsoid having a principal axis that is oriented horizontally and is generally coincident with the visual axis **219** of the eye **200**. The intersection of the visual axis **219** with the anterior surface **220** of the lens capsule **217** defines the anterior pole **221** of the crystalline lens **216**; and, the intersection of the visual axis **219** with the posterior surface **222** of the lens capsule **217** defines the posterior pole **223** of the crystalline lens **216**. The distance between the anterior pole **221** and the posterior pole **223** along the visual axis **219** defines the antero-posterior diameter **228** of the crystalline lens **216** and determines its antero-posterior thickness. Both the anterior and posterior surfaces, **220** and **222** of the crystalline lens **216** are generally convex, making the crystalline lens **216** a biconvex structure whose posterior convexity is generally steeper (having a smaller radius of curvature) than its anterior convexity.

The lens tissue of lens **216** within the lens capsule **217** is largely comprised of protein-laden cells that endow it with the property of transparency and also endow it with a degree of elasticity. As the crystalline lens **216** ages, the lens tissue within the lens capsule **217** becomes increasingly dense and decreasingly transparent centrally, changes that make it distinguishable into a higher density lens nucleus **225** and a circumscribing lower density lens cortex **226**.

Referring to FIG. 1C in light of FIG. 1A and FIG. 1B, the region of the eye having iris **211** as its base and cornea **204** as a vault or dome is called the anterior chamber **238** of eye **200**. The region of eye **200** formed by adding ciliary body **214** and crystalline lens **216** to anterior chamber **238** is called the anterior segment **239** of the eye **200**. The remainder of eye **200** is called its posterior segment **243**. In the healthy eye, the anterior segment is filled with a thin

fluid called the aqueous humor **244** and the posterior segment is filled with a gelatinous liquid called the vitreous humor **245**. The anterior surface of the vitreous humor is called the anterior hyaloid membrane **246**, in which there is formed a shallow concavity called the anterior hyaloid fossa **247** against which the posterior surface **222** of the lens capsule **217** is apposed.

Both cornea **204** and crystalline lens **216** of eye **200** are endowed with the capacity to refract incoming light arising from an object of regard. In general, cornea **204** has a fixed positive refractive power of about 45 diopters (D). Crystalline lens **216** has a minimum positive refracting power of about 20 D and has an additional variable positive refracting power that slowly declines to near zero with advancing age from a childhood maximum of about 15 D.

The refractive error of an eye is a measure of the degree to which an eye departs from an accepted standard of visual acuity when viewing optotypes or images at a distance of about 6 meters (20 feet) from an examinee. An eye without a refractive error is said to be emmetropic, and a person with emmetropic vision is called an emmetrope. An eye with any refractive error is said to be ametropic, and a person with ametropic vision is called an ametrope. An eye whose refractive error is such that its uncorrected visual acuity in all corneal meridians is superior at 6 m than it is when viewing objects less than 6 m away is said to be (spherically) hyperopic; and, a person with hyperopic vision is called a hyperope. An eye whose refractive error is such its uncorrected visual acuity in all corneal meridians **227** is inferior at 6 m than it is when viewing objects less than 6 m away is said to be (spherically) myopic; and, a person with myopic vision is called a myope. More complex forms of refractive error occur if the uncorrected visual acuity of an eye varies from one corneal meridian to another, in which case the eye is said have an

astigmatic refractive error.

Turning next to the subject of accommodation, an object of regard is generally regarded to be distant or "at far" if it is about 6 meters (20 feet) or more away from a subject. An object of regard is generally regarded to be "at near" if it is about 1/3 of a meter (about 14 inches) or closer to a subject. As indicated, *supra.*, accommodation generally refers to the processes by which the lenses of the eyes adapt to maintain an object of regard in sharp focus as it comes increasingly near to the eyes from an initially distant disposition.

Accommodation generally involves two known changes: a change in the refractive state of the eyes and a convergent change, i.e., a change in the angle that the visual axes of the eyes make with respect to one another in a horizontal plane. The refractive change of accommodation is mediated by the crystalline lenses **216** (FIG. 1A, FIG. 1B, FIG. 1C) of both eyes, which increase the convexity of their anterior and posterior surfaces **220** and **222** (FIG. 1A, FIG. 1B, FIG. 1C) and elongate their antero-posterior thicknesses **228** (FIG. 1B), thereby increasing their refractive plus power.

When the eyes of a person regard an object at far, they are said to be in a state of relaxed accommodation. The state of relaxed accommodation does not imply a state of disaccommodation. On the contrary, some tonic accommodation may be present. This is particularly true of refractively uncorrected hyperopes who may unconsciously enlist varying amounts of accommodative plus power at far to neutralize their hyperopia. As used herein, the state of disaccommodation refers to the minimal refractive plus power of the crystalline lens that is present when all accommodation has been eliminated by use of a cycloplegic pharmacologic agent.

When the eyes of a person regard an object at near they are said to be in a state of accommodation, the degree of which generally depends on the proximity of the object of regard to the eyes, with greater degrees of accommodation being invoked by the eyes as the object comes closer to them, until a limiting state of a person's maximum accommodation - - a person's accommodative amplitude - - has been reached.

In the state of relaxed accommodation, muscles of ciliary body **214** (FIG. 1A), to which zonules **215** (FIG. 1A) are connected, are in a state of relative relaxation, zonules **215** (FIG. 1A) are taut, and crystalline lens **216** (FIG. 1A), upon whose lens capsule **217** (FIG. 1A) zonules **215** (FIG. 1A) insert, is maintained at its narrowest antero-posterior diameter **228** (FIG. 1A), a state consistent with the shallowest convexity of its anterior and posterior surfaces, **220** and **222** (FIG. 1A), and lower refractive plus power .

In states of accommodation, muscles of the ciliary body **214** (FIG. 1A), to which zonules **215** (FIG. 1A) are connected, are in states of relative contraction, zonules **215** (FIG. 1A) are correspondingly relatively more slack, and crystalline lens **216** (FIG. 1A), upon whose lens capsule **217** (FIG. 1A) zonules **215** (FIG. 1A) insert, is maintained with its antero-posterior diameter **228** (FIG. 1A) increased and the convexity of its anterior and posterior surfaces **220** and **222** (FIG. 1A) increased. In states of accommodation, the refractive plus power of crystalline lens **216** (FIG. 1A) increases to converge divergent light, emanating from an object of regard at near, to a point of sharp focus upon the retina **210.**

When the gaze of the eyes falls upon an object that is about 6 meters (20 feet) or more from the eyes, the rays of light arising from the object of regard are generally parallel to one

another upon reaching the eyes and, in an emmetrope, the combined plus refractive power of cornea **204** (FIG. 1A) and crystalline lens **216** (FIG. 1A) will converge the parallel rays of light to a point of sharp focus upon retina **210** (FIG. 1A). The distant point at which an object of regard invokes a state of relaxed accommodation in a person is called the person's far point.

When the gaze of the eyes falls upon an object that is at or less than about 1/3 m (14 inches) from the eyes, the rays of light arising from the object of regard are generally divergent to one another upon reaching the eyes and, in an emmetrope, the combined plus power of cornea **204** (FIG. 1A) and crystalline lens **216** (FIG. 1A) must be augmented by the accommodation of crystalline lens **216** (FIG. 1A), so that the divergent rays of light are clearly focused to a point upon retina **210** (FIG. 1A).

The point at which an object of regard invokes the eyes' maximum accommodation in a person is called the person's near point. As indicated, *supra.*, the maximum accommodation that may be invoked by a person's eyes is called the person's accommodative amplitude. The accommodative amplitude, measured in diopters, is simply the reciprocal of the person's near point, measured in meters from the person's eyes. Accommodative amplitude diminishes with age in the approximate manner shown in Table 1.

Table 1. Approximate Accommodative Amplitude Associated with Age

Age	Accommodative Amplitude (D)
8	14
25	10
35	7
45	4
55	1

As used herein, the term dynamic accommodation refers to the intercurrent, time-dependent processes that transform an eye back and forth between any first state of accommodation to any second state of accommodation, which first and second states of accommodation are selectable from a range of accommodation defined by and inclusive of the state of disaccommodation and the state of accommodation corresponding to the accommodative amplitude of the eye.

Accompanying the refractive changes characteristic of accommodation is a nasal-ward (medial) rotation (version) of the eyes in a horizontal plane that makes the visual axes of the eyes, which are essentially parallel in distant vision, convergent in near vision. This nasal-ward rotation is called accommodative convergence.

The concurrent refractive and rotational changes that characterize accommodation are generally symmetrically bilateral phenomena. However, accommodation may be stimulated unilaterally. In this case, the eye that is being stimulated to accommodate - - the fixating eye - -

will provoke a symmetric refractive change in the lens of the contralateral, nonfixating eye. When unilateral stimulation causes the fixating eye to accommodate, the concurrent displacement of the visual axes of the eyes by accommodative convergence is effected entirely by the contralateral, nonfixating eye. That is, the visual system will accept the necessary convergent movement that must accompany the refractive change occurring in the lenses of the eyes during accommodation, as either the sum of two smaller nasal-ward rotations of both eyes or as an equivalent larger nasal-ward rotation of only one eye.

As a human being ages, the crystalline lens increases in volume with concomitant increases in anterior and posterior convexity. Additionally, its capacity to change its shape so as to further increase its anterior and posterior convexity and corresponding refractive plus power, i.e., its accommodative capacity, undergoes a corresponding decline. The point at which the accommodative capacity of the lens begins to fail marks the beginning of a period requiring "reading glasses" of increasing plus power in order to achieve clear focus at near. The condition of failing vision at near is called presbyopia.

FIG. 2 shows a first nonlimiting embodiment of the present invention. The first embodiment is an apparatus comprising an accommodative stimulation device **500**, an electromagnetic wave exposure device **100**, such as, for example, slit-beam projection lamp **122** emitting slit beam **156**, and an imaging device **400**, such as, for example, a Scheimpflug videography system **420**. The invention acquires imaging information about eye **200** by means of slit-beam projection lamp **122** and Scheimpflug videography system **420**, as accommodative stimulation device **500** simultaneously stimulates eye **200** to undergo at least one reversible accommodative transition from any first state of accommodation to any second state of

accommodation. The first and second states of accommodation are selectable from a range of accommodation defined by and inclusive of the state of disaccommodation and a state of accommodation corresponding to the accommodative amplitude of eye **200**.

Accommodative stimulation device **500** has an axis of projection **502** that is substantially perpendicular to visual axis **219** of eye **200**, along which axis of projection **502** an adjustable accommodative target **503** is projected through a system of Badal optics **504**, having a Badal optical axis **505**, coincident with axis of projection **502**, to strike a half-silvered mirror **506** lying in a mirror plane **507** that forms an angle of about 45 degrees with axis of projection **502** and visual axis **219** of eye **200**.

The stimulus to accommodation provided by accommodative stimulation device **500** simultaneously triggers dynamic imaging, by operationally coupled imaging device **400**, of anterior segment **238** (FIG. 1C) of eye **200**, in general, and of crystalline lens **216** (FIG. 1B), lens capsule **217** (FIG. 1B), zonules **215** (FIG. 1B), ciliary body **214** (FIG. 1A), and anterior hyaloid membrane **246** (FIG. 1C) of eye **200**, in particular, which imaging continues as eye **200** is stimulated by accommodative stimulation device **500** to undergo one or more predetermined dynamic accommodative transitions.

As shown in FIG. 3, conventional imaging of eye **200** typically uses a slit lamp biomicroscope **101** with an imaging device **400** such as, for example, a conventional still film macrophotography camera **600**, effectively directed through optics of biomicroscope **118**, and having a conventional imaging lens system **601** with a conventional imaging lens axis **602** that is substantially aligned with visual axis **219** of eye **200**.

Slit beam **156** is used to illuminate structures on or within eye **200**, and is generally oriented to make an angle with visual axis **219** in a horizontal plane ranging between about 20 degrees and 80 degrees. The object planes available for sharp focusing in conventional imaging of eye **200**, i.e., the planes containing an object on or within eye **200** that may be clearly imaged by conventional still film macrophotography camera **600**, generally comprise planes other than anatomical sagittal plane **240** shown in FIG. 2 and in FIG. 1A.

As shown in FIG. 4, unlike conventional imaging of eye **200**, Scheimpflug imaging of eye **200** is a technique that uniquely enables imaging of structures of eye **200**, including crystalline lens **216**, in anatomic sagittal plane **240**, extending from anterior surface **220** of lens capsule **217** to posterior surface **222** of lens capsule **217**. The unique advantage of Scheimpflug imaging over conventional imaging of the eye **200** is that images of, about, and within crystalline lens **216** along visual axis **219** of eye **200** within sagittal plane **240** can be captured.

In FIG. 4, Scheimpflug imaging device **411** has a Scheimpflug imaging medium **401** such as, for example, still or motion picture film, or a still or motion picture digital medium such as, for example a CCD array, oriented with its imaging surface defining a Scheimpflug imaging plane **402** that is generally coincident with back surface **403** of Scheimpflug imaging device body **404**. Scheimpflug imaging device body **404** generally has the shape of a rectangular parallelepiped, whose front surface **405** opens onto bellows **406**. Bellows **406** terminates in lens housing **422**, supporting Scheimpflug imaging lens system **407**, shown for the sake of simplicity as a single lens in FIG. 4, defining Scheimpflug imaging lens plane **408**.

In FIG. 4, eye **200** is shown schematically in an anatomic sagittal view. Sagittal plane **240**

contains visual axis **219** and intersects anterior surface **220** of lens capsule **217** and posterior surface **222** of lens capsule **217**. In accordance with the Scheimpflug Principle, in order for an object, such as cross-sectional image of crystalline lens **216** lying in sagittal plane **240**, to be sharply focused as a corresponding image on Scheimpflug imaging medium **401**, lying in Scheimpflug imaging plane **402**, Scheimpflug imaging plane **402**, Scheimpflug imaging lens plane **408** and sagittal plane **240** must intersect at common line of intersection **410**. In the particular case in which Scheimpflug imaging plane **402** and sagittal plane **240** intersect at common line **410** to form an approximate right angle, that is approximately halved by Scheimpflug imaging lens plane **408**, a 1:1 image to object ratio is also achieved.

The Scheimpflug Principle determines the degree to which Scheimpflug lens plane **408** of exemplary Scheimpflug imaging device **411** must be rotated (tilted) away from its conventional parallel orientation to Scheimpflug imaging plane **402** of exemplary Scheimpflug imaging device **411** in order to sharply focus on Scheimpflug imaging plane **402** an object lying in an object plane, i.e., anatomical sagittal plane **240**, that is not parallel to Scheimpflug imaging plane **402**.

In the present invention angle α, formed by the intersection of Scheimpflug imaging lens plane **408** and anatomical sagittal plane **240** when both planes also intersect Scheimpflug imaging plane **402** (in satisfaction of the Scheimpflug Principle) is called the Scheimpflug angle.

In the present invention, when Scheimpflug imaging lens plane **408** and anatomical sagittal plane **240** intersect Scheimpflug imaging plane **401**, and Scheimpflug imaging lens plane **408** forms angle α with anatomical sagittal plane **240**, then Scheimpflug imaging lens plane

408, anatomical sagittal plane **240**, and Scheimpflug imaging plane **401** are said to be in Scheimpflug alignment.

When, as shown in FIG. 2, electromagnetic wave exposure device **100** comprises slit-beam projection lamp **122** emitting slit beam **156**, whose axis of projection is coincident with visual axis **219** of eye **200**, and imaging device **400** comprises Scheimpflug videography system **420**, accommodative changes occurring in and about crystalline lens **216** in sagittal plane **240** of eye **200** are dynamically imaged without loss of Scheimpflug alignment owing to accommodative convergence, as explained hereinabove.

FIG. 5 is a schematic illustration showing a perspective view of accommodative stimulation device **500** common to all embodiments of the present invention. In FIG. 5, accommodative stimulation device **500** comprises a support member **531** supporting an accommodative target projection subsystem **501** having axis of projection **502** that is substantially perpendicular to visual axis **219** of eye **200**. Adjustable accommodative target **503** is projected along axis of projection **502** through a multi-lens Badal optical system **504**, having a Badal optical axis **505** coincident with axis of projection **502**, to strike a half-silvered mirror **506** lying in a mirror plane **507** that forms an angle of about 45 degrees with both axis of projection **502** and visual axis **219** of eye **200**.

Accommodative target projection subsystem **501** comprises a projection platform **508** attached to a computer-controlled motorized carriage **522** that is moveable along an axis of travel **523** parallel to a linear scale **524**, the limits of which define a Badal space **525**. Computer-controlled motorized carriage **522** may be caused to move bidirectionally along axis of travel

523, within Badal space **525**, by a suitable driving mechanism, such as, for example, a computer-controlled servo-motor **527** driving a belt **528** that loops about a driving pulley **529**, to precisely displace carriage **522** to which belt **528** is operationally attached by a linkage **530**.

Alternatively, computer-controlled motorized carriage **522** may be caused to move bidirectionally along axis of travel **523**, within Badal space **525**, by, for example, a driving engine in the from of an on-board servo-motor that is subject to wireless computer control. The driving mechanism is configured to make computer-controlled motorized carriage **522** moveable between any point in Badal space **525** within a period of time that is substantially less than the minimum response time for accommodation that invokes the accommodative amplitude of eye **200**.

Computer-controlled motorized carriage **522** may be constrained to move along axis of travel **523** by, for example, having it ride upon at least one traveling rod **526**, as shown in FIG. 5, or, as another example, computer-controlled motorized carriage **522** may be constrained to move along axis of travel **523** by having it engage one or more linear channels or tracks (not shown in FIG. 5), or by being suspended from a monorail or similar rigid pathway (not shown in FIG. 5).

Linear scale **524** is calibrated in diopters of accommodative stimulus, or a substantially equivalent measure of accommodation, provided by projection platform **508** of accommodative target projection subsystem **501** at each position projection platform **508** makes along axis of travel **523**. Axis of travel **523** and linear scale **524** are both substantially parallel to axis of projection **502**, and both are also substantially perpendicular to visual axis **219** of eye **200**.

Multi-lens Badal optical system **504** is effectively disposed so as to place corneal vertex

229 of eye **200** at a distance about equal to the secondary focal length of Badal optical system **504**, thereby assuring that:

[i] the degree of accommodation of eye **200** stimulated by adjustable accommodative target **503** is linearly related to the distance of moveable projection platform **508** from Badal optical system **504**; and,

[ii] adjustable accommodative target **503** seen by eye **200** does not change size, i.e., the apparent size of adjustable accommodative target **503** perceived by eye **200** will remain constant and be independent of the position of projection platform **508**. This feature has the salutary effect of eliminating any changing in size of adjustable accommodative target **503** as a stimulus to accommodation in eye **200**.

Projection platform **508** of accommodative target projection subsystem **501** shown in FIG. 5 is shown in greater detail in FIG. 6. In FIG. 6, projection platform **508** is shown in an exemplary hollow cylindrical conformation. Projection platform **508** has a central longitudinal axis **509**, an illuminating segment **510**, an internal segment **511**, and a projecting segment **512**. Central longitudinal axis **509** of projection platform **508** defines axis of projection **502** (FIG. 2 and FIG. 5).

Illuminating segment **510** of projection platform **508** is adapted to receive an energizeable source of light **513** outputting light of adjustable intensity. Internal segment **511** of projection platform **508** is adapted to receive at least one member of a set of exchangeable target-image-forming stencils, such as, for example, target-image-forming stencil **514**, that may, for example, be arrayed circumferentially along a disk **516**, having multiple apertures **517** adapted to accept a

variety of stencils forming, for example, accommodative optotypes, such as accommodative optotype **518**, or a variety of stencils forming, for example, accommodative figurative target-images, such as accommodative figurative target-image **519**, as shown in FIG. 5. Alternatively, exchangeable target-image-forming stencils **514** may, for example, be arrayed linearly along a rectangular strip (not shown in FIG. 5) having multiple apertures adapted to accept a variety of stencils forming accommodative optotypes or figurative target-images.

Projecting segment **512** of projection platform **508** is adapted to house a system of adjustable lenses **520**, to correct any refractive error of eye **200**, and to transmit light passed by target-image-forming stencil **514** from light source **513** through Badal optical system **504** and thence onto half-silvered mirror **506** (FIG. 5 and FIG. 2).

FIG. 7 shows first nonlimiting exemplary embodiment of the invention is greater detail. In FIG. 7, accommodative stimulation device **500** is operationally coupled to a modified slit lamp assembly **150,** so that when an examinee's gaze is properly oriented, visual axis **219** of eye **200** is perpendicular to axis of projection **502**, and corneal vertex **229** of eye **200** is effectively disposed at a distance equal to the secondary focal length of Badal optical system **504** of accommodative target projection subsystem **501**. Projection platform **508** of accommodative target projection subsystem **501** is in the form of a generally cylindrical hollow projection tube.

Modified slit lamp assembly **150** as incorporated into first nonlimiting exemplary embodiment of the invention includes a head rest frame **147** mounted on a table **120** or other suitable support. Head rest frame **147** has a vertically adjustable chin support **102** extending horizontally between paired, parallel, upright, telescoping columns **103**, thereby raising or

lowering visual axis **219** of eye **200** to the level of a slit beam **156**. An examinee's forehead is supported by forehead band **146**.

A carriage **107** is mounted to be movable along table **120** relative to head rest frame **147** by means of a spherical element (not shown in FIG. 7) mounted in carriage **107** and riding on the surface of table **120**, carriage **107** being laterally slidable along a shaft **108** having pinions **109** at its ends engageabley riding on parallel racks **110** formed in housings **111** mounted on surface of table **120**. A joystick **112** extends from carriage **107** to be moved by an examiner to provide anterior and posterior movement of carriage **107** along parallel racks **110** and left-right lateral movement of carriage **107** along shaft **108**.

Mounted on carriage **107** is a pivot assembly **113** comprising a hub **114** having an arm **115** extending transversely therefrom and cooperating with a vertical adjustment knob **116** for raising and lowering pivot assembly **113**. Pivot assembly **113** includes imaging device arm **160** carrying a Scheimpflug Videography System **420** on a horizontally rotatable first platform **162** supported by a vertical column **164** pivotably mounted on the terminus of imaging device arm **160**. A horizontal stalk **163** rotatably inserts into a vertical column **164** and extends from vertical column **164** to support a horizontally rotatable second platform **165** at free end **166** of horizontal stalk **163**.

Pivot assembly **113** also includes an L-shaped slit-beam illumination arm **161** carrying a horizontally oriented slit beam projection lamp **122**. Imaging device arm **160** and L-shaped slit-beam illumination arm **161** are pivotally mounted on a common vertical pivot pin (not shown in FIG.7), supported by hub **114** and pivot assembly **113**, such that Scheimpflug videography

system **420** and slit beam projection lamp **122** are concentrically horizontally pivotal about a common vertical axis defined by columnar pivot assembly **113**.

Scheimpflug Videography System **420**, mounted on horizontally rotatable first platform **162**, comprises a video imaging device **421**, such as, for example, a high resolution (1024 by 1024 pixel) Dalsa D4 digital camera, coupled to a bellows **406** that opens into a lens housing **422**, carried by horizontally rotatable second platform **165**, for support of an imaging lens (not shown in FIG. 7), such as for, example, a Nikon Nikkor Macro Lens with an objective of 1.75:1.

Image device arm **160**, horizontally rotatable first platform **162** carrying video imaging device **421**, horizontal stalk **163**, and horizontally rotatable second platform **165** carrying lens housing **422** are independently adjustable to enable the imaging lens (not shown in FIG. 7) that is supported by lens housing **422** in imaging lens plane **408**, to be horizontally rotated with respect to imaging plane **402** and sagittal plane **240** to provide a Scheimpflug alignment of these planes.

Slit beam projection lamp **122** has a variable intensity lamp (not shown in FIG. 7) arranged to direct light through an internal adjustable slit optical system (not shown in FIG. 7) comprising lenses, filters, diaphragms and apertures, whose arrangement fashions light emitted from the variable intensity lamp into slit beam **156**, having variable height and width, that is directed through slit aperture **154** of slit beam projection lamp **122** to arrive at eye **200** directed along a slit beam axis substantially coincident with visual axis **219** of eye **200**. Slit aperture **154** can be rotated to vertically or horizontally orient slit beam **156**.

When slit beam **156** is directed into eye **200**, as shown in FIG. 1C, it sequentially intercepts, from anterior to posterior, the cornea **204**, the aqueous humor **244**, the anterior surface

220 of the lens capsule **217**, the crystalline lens **216**, the posterior surface **222** of the lens capsule **217**, the anterior hyaloid membrane **246** and the anterior aspect of vitreous humor **245**, all shown in FIG. 1C.

If slit beam **156** is directed into the anterior aspect of eye **200** so as to make an angle with visual axis **219** of eye **200** that is greater than or equal to zero degrees but less than ninety degrees, it will illuminate the foregoing tissues, rendering them visible in the plane that the slit beam forms as it intersects each tissue.

When using first embodiment of the invention, an examinee's head is supported by a headrest frame **147** having a vertically adjustable chin support **102** and a forehead rest **146** so that the examinee's head is not allowed to move. Thereafter, an examiner adjusts parallel upright telescoping columns **103** to move chin support **102** up and down, thereby bringing eye **200** into a desired examining position. The orientation of the visual axis **219** of eye **200** may be maintained during imaging of dymamic accommodation by instructing an examinee to maintain his or her gaze at adjustable accommodative target **503** reflected onto visual axis **219** by half-silvered mirror **506** disposed in mirrror plane **507**.

By operationally coupling modified slit lamp assembly **150** with Scheimpflug videography system **421** to accommodative stimulation device **500**, imaging information accompanying dynamic accommodation may be captured to yield valuable information about the optics of accommodation that may, *inter alia*, be useful in the development and perfection of intraocular lenses having the capacity to emulate dynamic accommodation. Furthermore, by operationally coupling modified slit lamp assembly **150** with Scheimpflug videography system

421 to accommodative stimulation device **500**, imaging information regarding refractive errors that accompany presbyopia, cataractogenesis and other crystalline lens pathological conditions may be captured.

A second nonlimiting exemplary embodiment of the invention is shown in FIG. 8, a schematic illustration in which accommodative stimulation device **500** is interfaced with an exemplary wavefront aberrometer **800** that measures optical aberrations of eye **200**. Exemplary wavefront aberrometer utilizes a Shack-Hartmann sensor **811**. A source beam **802** of infrared or near infrared radiation emitted from a beam projector **803**, such as, for example, an infrared laser or light emitting diode, is projected, via an optical coupler **805** onto retina **210** of eye **200** through cornea **204** and crystalline lens **216**. Efferent beam **804** of radiation is then reflected and scattered from retina **210** back through crystalline lens **216**, cornea **204**, appearing to emerge from an exit pupil (not shown in FIG. 8) in exit pupillary plane **213exPP**, and carrying information relating to optical aberrations of eye **200** such as, for example, chromatic aberrations, spherical aberrations, lenticular aberrations, monochomatic aberrations, and, in principle, dynamic accommodative aberrations

If, for example, eye **200** is emmetropic, without aberrational error, the wavefront profile of efferent beam **804** at exit pupillary plane **213exPP** is planar. For a myopic or hyperopic eye without aberrational error, the wavefront profile of efferent beam **804** at exit pupillary plane **213exPP** is spherical. For an eye with aberrational errors, the wavefront profile of efferent beam **804** at exit pupil plane **213exPP** is irregularly distorted. Wavefront aberrometer **801** measures

the wavefront profile of efferent beam **804** at exit pupil plane **213exPP** to determine optical aberrations that comprise higher order refractive errors of eye **200**.

The wavefront of efferent beam **804** at exit pupil plane **213exPP** passes through half-silvered mirror **506** of accommodative stimulation device **500**, disposed in mirror plane **507** oriented at 45 degrees to projection axis **502**, and optical coupler **805**, to optical relay module **808**. Optical relay module **808** relays the wavefront of efferent beam **804** from exit pupillary plane **213exPP** of eye **200** to conjugate plane **809PP** at Shack-Hartmann sensor **811**.

Shack-Hartmann sensor **811** comprises a lenslet array (not shown in FIG. 8) that is disposed at plane **809PP** conjugate to exit pupillary plane **213exPP**. The lenslet array passes efferent beam **804** into lenslet sub-apertures (not shown in FIG. 8), and forms a Shack-Hartmann spot pattern (not shown in FIG. 8) at a focal plane of the lenslet array. The Shack-Hartmann spot pattern carries optical aberrational information of the wavefront profile of efferent beam **804**. Detector **807** detects the Shack-Hartmann spot pattern and outputs a digital signal that is applied as input to a computer analyzer **806**. Computer analyzer **806** extracts aberration information from the wavefront profile, and calculates higher order refractive errors of eye **200** in accordance with any one of a number of methods using the digital signal input by detector **807**.

By operationally coupling wavefront aberrometer **800** to accommodative stimulation device **500**, dynamic higher order refractive errors that accompany dynamic accommodation may be measured to yield valuable information about the optics of accommodation that may, *inter alia*, be useful in the development and perfection of intraocular lenses having the capacity to emulate dynamic accommodation. Furthermore, by operationally coupling wavefront

aberrometer **800** to accommodative stimulation device **500**, dynamic higher order refractive errors that accompany presbyopia, cataractogenesis and other crystalline lens pathological conditions may be isolated, quantified and established in mathematically functional relationships.